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Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest

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Abstract

We present a conceptual biogeomorphic model of riparian forest development in montane river networks. The role of physical process in driving the structure, composition, and spatial distribution of riparian forests is examined. We classify the drainage network into disturbance process-based segments including: (1) debris-flow and avalanche channels, (2) fluvial and debris-flow channels, and (3) fluvial channels. Riparian forests are shown to be significant in the development of channel morphology through the stabilization of active floodplains and as sources of large woody debris (OLWD). LWD is operationally defined as wood > 0.1 m diameter and > 1 m length. LWD plays a key role in the development of montane riparian forests. LWD deposited in the active channel and floodplain provides sites for vegetation colonization, forest island growth and coalescence, and forest floodplain development. Riparian forest patterns parallel the distribution of hillslope and fluvial processes through the network. Riparian forest structure, composition, and spatial distribution through the network are driven by the major disturbance processes including: (1) avalanches, (2) debris-flows, and (3) flooding. Riparian forest patterns also reflect the action of LWD in the organization and development of forested floodplains in gravel bedded montane river networks. The focus of our examples are montane river networks of the Pacific Northwest, USA.

1. Introduction

The structure, composition, and spatial distribution of riparian forests throughout montane river networks is driven by hillslope and fluvial processes (Oliver et al., 1985; Harris, 1987; Naiman et al., 1992). In turn, riparian forests play a significant role in the development of channel morphology through the stabilization of active floodplains and as sources of channel modifying LWD (Keller and Swanson, 1979; Grant et al., 1990). LWD deposited upon the active channel and floodplain creates conditions necessary for plant colonization within an otherwise inhospitable alluvial environment (Sedell et al., 1988). Riparian forest islands established in association with accumulations of LWD may increase in size and coalesce with other LWD associated islands forming a larger forested floodplain mosaic. In this article we discuss the role of LWD in the development of montane riparian forests and present a conceptual model of this biogeomorphic process.

2. The riparian forest — a process definition

The riparian forest is the linkage between lotic and terrestrial ecosystems in forested landscapes. The riparian forest influences channel form and stream function by contributing particulate organic matter and LWD, by providing shade, bank stability, sites for storage of organic matter, sediment and water, and by regulating

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the movement and transformation of nutrients (Gregory et al., 1991).

Riparian forests extend laterally from the active channel to include the active floodplain, and adjacent wetland areas. The active channel is defined by the lower limit of continuous terrestrial vegetation (Church, 1992). The active floodplain is located between the active channel at bankfull stage and adjacent terrace or hillslopes (Dunne and Leopold, 1978). Forests contributing organic matter, leaves, branches, and LWD directly to the active channel or floodplain are included in this definition of riparian forest. The development of montane riparian forests is driven by network wide disturbance processes (Brinson, 1990; Gregory et al., 1991). We define disturbance following White and Pickett (1985) as: any relatively discrete event in time that disrupts ecosystem, community, or population structure, and that changes resources, availability of substratum, or the physical environment. The central points of our definition are that montane riparian forested landscapes are highly variable in time and space, and that their community, population, and ecosystem characteristics need to be understood within the context of geomorphic processes.

The physical and vegetation characteristics of the streamside area differ from those upslope because of frequent inundation, soil saturation, and physical disturbance of streamside vegetation due to flood flows, mass soil movements or ice damage (Hickin, 1984; Brinson, 1990; Gregory et al., 1991). The diverse vegetation supported by riparian landscapes in the Pacific Northwest (Campbell and Franklin, 1979) is the product of those disturbance events interacting with spatially heterogeneous environmental conditions (Oliver et al., 1985; Agee, 1988). In forested montane river networks physical disturbances such as shearing forces (i.e., debris-flow, flooding, avalanche, and ice flow), soil water anoxia, drought, sedimentation, windthrow, and fire collectively contribute to riparian forest age, composition, structure and dynamics. Physical disturbance processes vary systematically through the drainage network and are reflected in the riparian forest structure and composition (Fig. 1). These characteristic physical and biologic patterns lend themselves to classification of channel processes and riparian vegetation.

3. A channel network perspective

The classification of riparian forests and physical processes is useful for describing the role of LWD in forest development through the channel network. Montane riverine networks can be classified by stratifying the network into disturbance process-based segments (Fig. 1): (1) debris-flow and avalanche channels, (2) fluvial and debris-flow channels, and (3) fluvial channels (D. Montgomery, Univ. of Washington, pers. commun., 1994). Active channel and floodplain morphology is influenced by the degree of valley wall confinement. We define channel confinement as the ratio of valley floor width to bankful channel width. This definition integrates valley morphology with alluvial channel process such that riparian forest dynamics may be compared and contrasted through the network. This general physical classification uses both network position, as defined by fluvial and hillslope process, and the attendant dominant riparian forest disturbance type (i.e., avalanche, debris flow, or fluvial) to characterize riparian forest patterns. Avalanche dominated riparian forests occur along steep narrow channels of the alpine headwaters of the network. Given the slope and aspect configurations, these areas are frequently disturbed by avalanches as is evidenced by the persistent long narrow patches of riparian species such as sitka alder (*Alnus sinuata*) growing parallel to these channels. Debris-flow channels, affected by scouring and deposition, are characterized by slopes >0.05 (Benda and Dunne, 1987; Reneau and Dietrich, 1987). Debris-flows may disturb riparian vegetation resulting in the characteristic long linear vegetation patches parallel to the channel (Grant et al., 1984). Debris-flow return intervals in the Pacific Northwest, USA have been estimated to be once in 750–1500 years for first-and second-order channels in the Oregon Coast Range (Benda and Dunne, 1987) and once in 500 years for first-order channels in the central Oregon Cascades (Swanson et al., 1985). For slopes <0.05, alluvial channel morphology and riparian forest structure, composition, and spatial distribution are primarily influenced by floods.

4. The role of large woody debris in forested floodplain dynamics

LWD is an important structural component of Pacific Northwest streams (Naiman and Sedell, 1979; Harmon

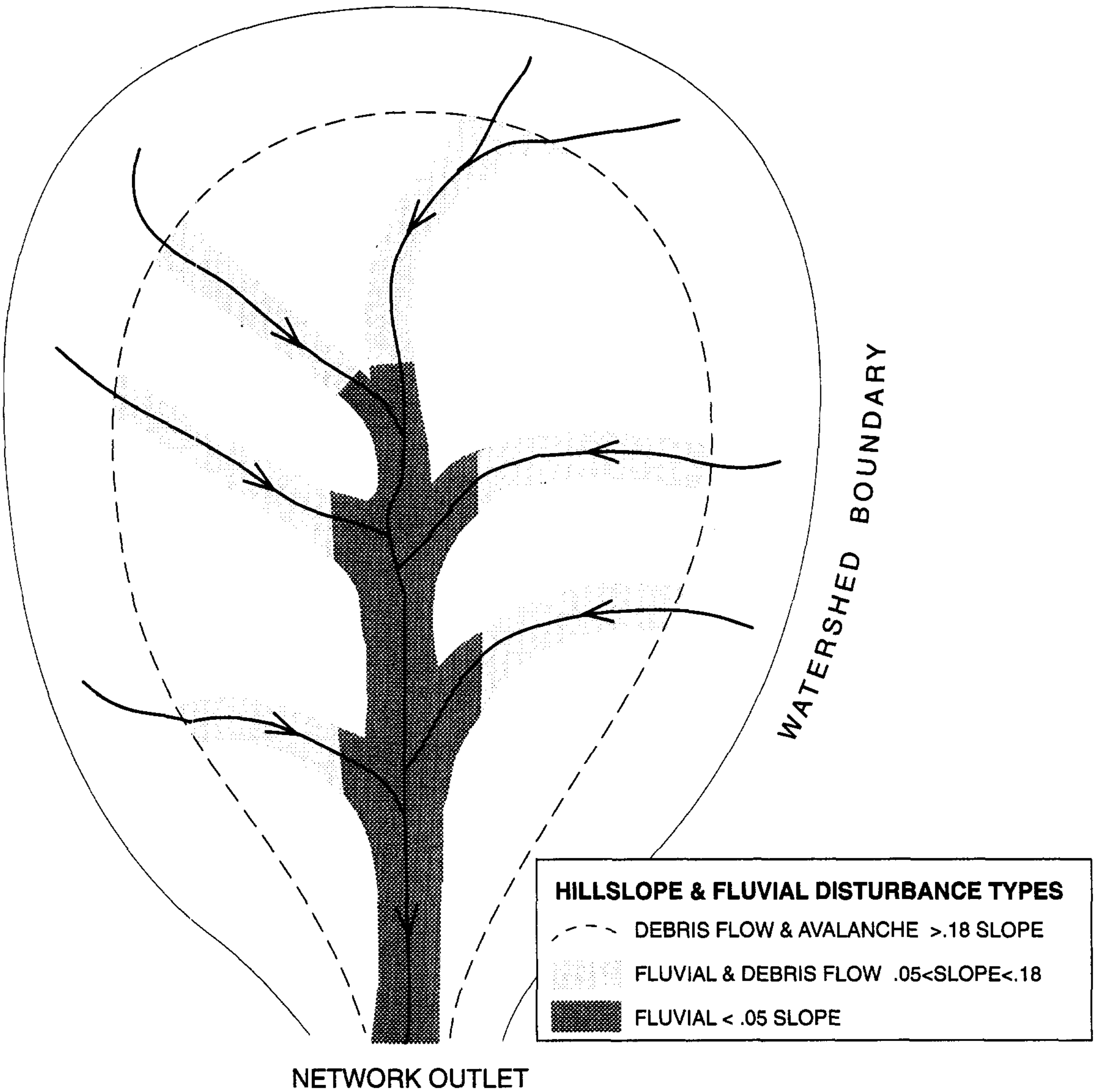

Fig. 1. Watershed distribution of dominant hillslope and fluvial disturbance types, Olympic Mountains, USA. Disturbance process slope values are approximate and ranges overlap (i.e., Fluvial and debris flow processes are not mutually exclusive) (Benda and Dunne, 1987; Montgomery and Buffington, 1993). Fire in these watersheds primarily affects uplands but will enter the riparian forest depending upon the disturbance magnitude and the aerial extent of the riparian zone (Agee, 1988). Wind damage occurs throughout the river network but has yet to be quantitatively studied in the Pacific Northwest.

et al., 1986). LWD is a primary determinant of channel morphology, forming pools and creating waterfalls, regulating the transport of sediment, gravel, organic matter and nutrients, and providing habitat and cover for fish and other aquatic biota (Bisson et al., 1987). Retention of sediment, organic matter, and nutrients by large woody debris influences the successional dynamics of riparian vegetation by providing new surfaces for the establishment of ovegetation (Sedell et al., 1988). The relative importance of this process as well as the distribution, amount and functions performed by LWD vary with channel size (Bilby and Ward, 1991). LWD in the active channel or floodplain creates low velocity zones where fluvially transported sediment and organic matter collect. These depositional sites provide locations for the establishment of pioneer plant species ini-

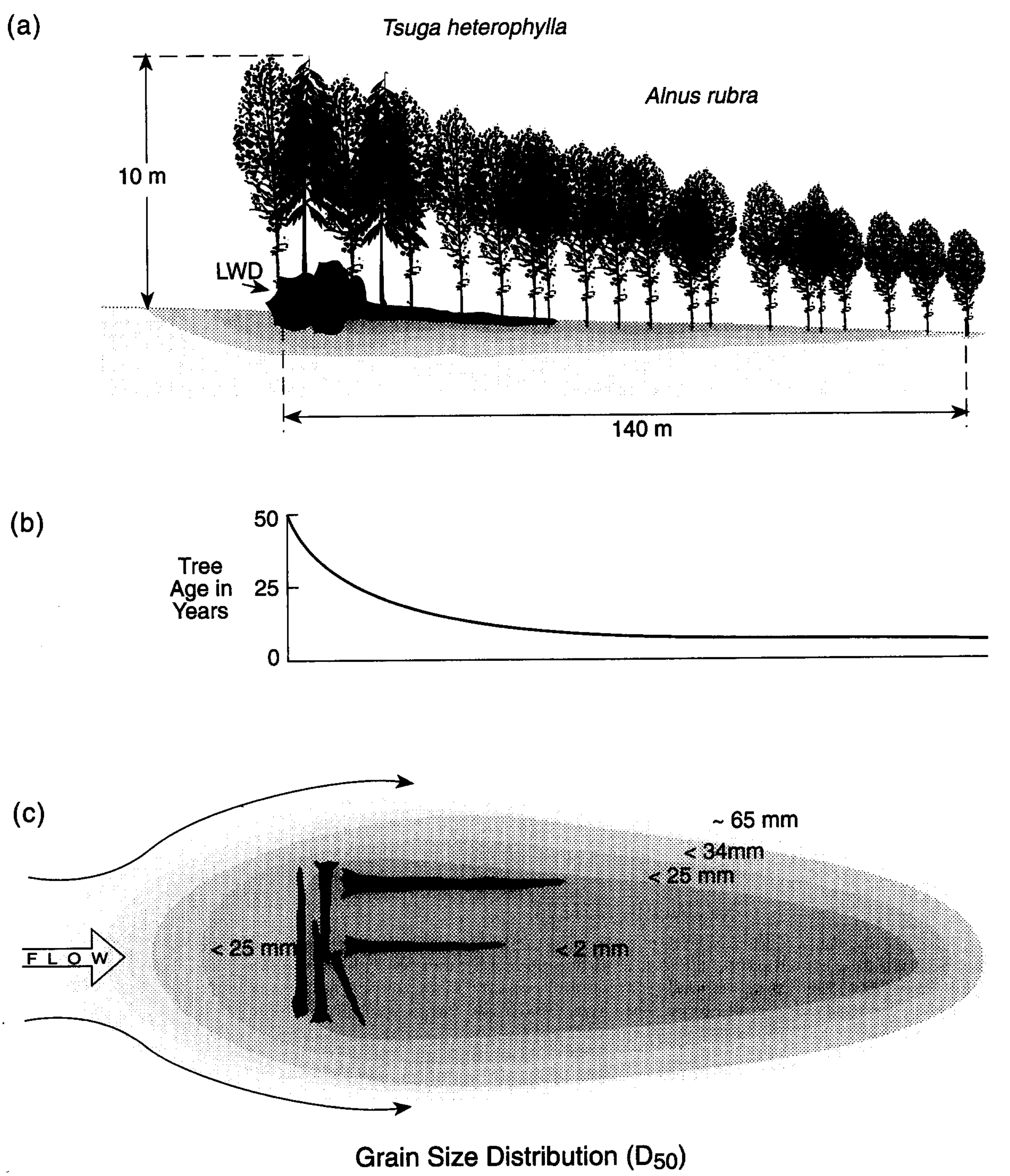

Fig. 2. (a) Large woody debris accumulation and forest island development along the mainstream of the Queets River (Fetherston and Naiman, unpubl. data). Forest island growth rate has been measured with aerial photography and standard dendrochronological methods (Fritts, 1976). (b) Distribution of tree ages longitudinally through the forest island. (c) Forest island surface grain size distribution (D_{50}). Grain size analysis follows Dunne and Leopold (1978).

tiating vegetation development (Sedell et al., 1988; Fig. 2). Established patches of vegetation may be removed during hillslope or fluvial disturbances, recruiting LWD to the active channel and providing new sites for establishment of vegetation.

5. Distribution in channel networks

Generally, small channels tend to contain abundant woody debris. In larger channels wood is more easily transported, leading to a reduction in LWD frequency due to flushing of smaller pieces and clumping of remaining LWD (Fig. 3). The size of LWD accumulations increases downstream while the frequency decreases (Swanson et al., 1982). LWD accumulations in rivers may increase channel width, facilitate the development of depositional features, and may encourage the development of meander cutoffs (Keller and Swanson, 1979). Large channel features of this type typically are not associated with LWD in small to mid-sized channels (Bilby and Ward, 1991), except at the terminus of debris torrents where large accumulations of LWD and sediment often are found (Swanson et al., 1985).

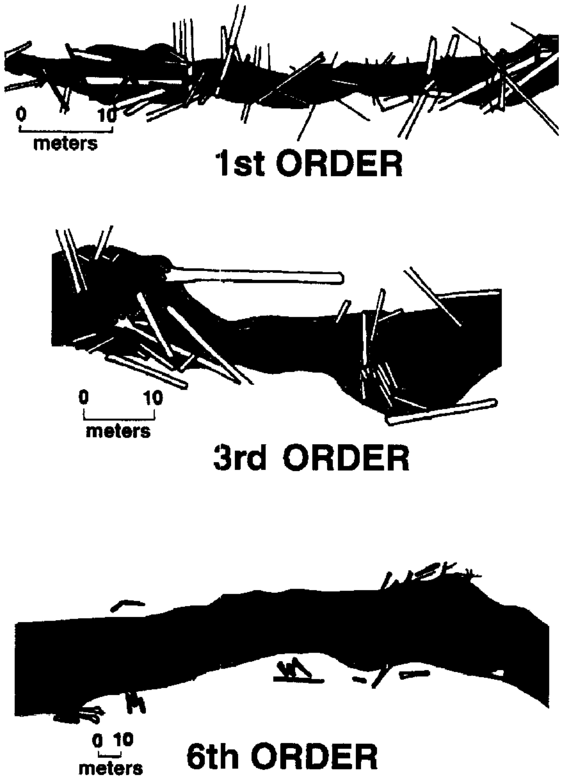

Fig. 3. Distribution and abundance of LWD in channels of varying size in the Cascade Mountains of Oregon (from Bisson et al., 1987, based on data from Swanson et al., 1982).

The amount and distribution of LWD is also influenced by the species composition of the riparian vegetation. Species which achieve large size produce more stable, longer-lived debris than smaller species. Thus, streams flowing through mature stands of conifer in the Pacific Northwest tend to contain larger amounts of wood with larger average sized pieces than channels located in younger communities, often dominated by smaller, hardwood species (Bilby and Ward, 1991). Conifer-derived LWD not only tends to be larger than hardwoods, thus reducing the probability of flushing downstream, but decay rates are significantly lower, increasing longevity in the system (Harmon et al., 1986). Both of these factors tend to increase LWD amounts in channels flowing through forests dominated by conifers.

6. Input mechanisms

Mechanisms of LWD delivery to streams can be segregated into chronic and episodic delivery processes (Bisson et al., 1987). Chronic mechanisms include the regular introduction of wood as a result of natural tree mortality or gradual bank undercutting. These processes tend to add small amounts of wood at frequent intervals. In contrast, episodic inputs, including catastrophic windthrow, fire or severe floods, occur infrequently but can add large amounts of wood to the channel network.

The zone from which LWD is supplied to the channel varies as a function of the species composition of the riparian vegetation, topography of the streamside area, characteristics of the channel and direction of the prevailing wind (Steinblums et al., 1984; Grette, 1985; Murphy and Koski, 1989). Much of the LWD in unconstrained channels is introduced by undercutting of trees on the bank (Grette, 1985; Murphy and Koski, 1989). Input to small-or medium-sized constrained channels tends to be dominated by windthrow (Keller and Swanson, 1979). Additional input mechanisms for LWD include transport from upstream reaches during flood flows or mass failures (Swanson et al., 1982).

Both empirical and theoretical analyses of the probability of input of LWD to a channel as a function of distance from the streambank have been developed (Murphy and Koski, 1989; Robison and Beschta, 1990; Van Sickle and Gregory, 1990; Andrus and Lorenzen, 1992). In general, these analyses illustrate that the primary zone of input is equivalent to the height of the tallest trees growing along the stream. The probability of a tree within the riparian zone entering the stream when it falls decreases with distance from the channel edge and varies by species due to differences in tree height (Van Sickle and Gregory, 1990; Andrus and Lorenzen, 1992). In general, 70% to 90% of the riparian input of LWD occurs within 30 m of the channel edge. The additional 10% to 30% is provided from beyond this distance. However, as riparian stands develop more late-successional characteristics, including a higher component of conifer and taller trees, proportionately more input will occur from beyond 30 m (Van Sickle and Gregory, 1990).

7. Formation of depositional sites

Large woody debris influences the routing of sediment and particulate organic matter through channel networks by creating areas of low shear stress where material can be stored. In small, high gradient streams, the primary method by which LWD decreases shear stress is through the formation of step-pools (Marston, 1982; Grant et al., 1990). A small, low gradient area is created upstream from the LWD and step-pool downstream. In channels less than 7 m wide in western Washington, more than 15% of the total drop in elevation of a stream may be accounted for by summing the heights of LWD formed steps (Marston, 1982; Bilby and Ward, 1989). Steps formed by LWD become rarer in larger systems, accounting for only 5% of the elevation change in channels from 7–10 m wide. In channels wider than 20 m step-pools formed by LWD are rare. In the larger systems LWD creates depositional sites by forming regions of reduced shear stress downstream from the wood accumulation or between the LWD and the stream bank (Keller and Swanson, 1979).

A substantial proportion of particulate material stored in a channel may be associated with LWD (Naiman and Sedell, 1979; Bilby and Likens, 1980; Bilby, 1981; Megahan, 1982). LWD was responsible for storing 87% of the sediment in the channel of a small stream in New Hampshire (Bilby, 1981), and 47% in seven small Idaho streams (Megahan, 1982). Removal of wood from a 250 m reach of a stream in the Oregon Coast Range released 5250 m^3 of sediment (Beschta, 1979). Large increases in sediment movement also were associated with removal of redwood (*Sequoia sempervirens*) LWD from a northern California stream (Macdonald and Keller, 1987).

Depositional sites associated with LWD in small streams tend to be small but frequent. In channels less than 7 m wide flowing through old-growth vegetation in western Washington, 39% of the LWD pieces were associated with sites of sediment deposition (Fig. 3; Bilby and Ward, 1989). The frequency with which LWD formed depositional sites decreased with increasing stream size, with 26% of the pieces accumulating sediment in channels from 7 m to 10 m wide and 19% in channels over 10 m wide (Bilby and Ward, 1989). Proportion of the channel covered by sediment associated with LWD also decreased with increasing stream size (Bilby and Ward, 1991). Depositional sites formed by LWD covered 19% of the streambed in channels 5 m wide, decreasing to 3% in channels 15 m wide. The decrease was due to a decrease in the amount of LWD and a decrease in the proportion of pieces forming depositional areas.

Although LWD depositional sites decrease in frequency with increasing channel width in small to medium streams, the average size of the depositional sites increases (Bilby and Ward, 1989). This is due in part to the narrower channel, higher gradient, and step-pool morphology of small streams, which tends to limit the size of depositional areas relative to those formed downstream from LWD accumulations in channels with a pool–riffle or plane-bedded morphology (Montgomery and Buffington, 1993). In addition, larger LWD pieces or accumulations of LWD create larger depositional areas. Average piece size and frequency of large accumulations of LWD increases with increasing channel size through the network (Bilby and Ward, 1991).

8. Vegetation colonization and establishment — the role of LWD

The change in size, frequency, location, and longevity of depositional sites formed by LWD influences the

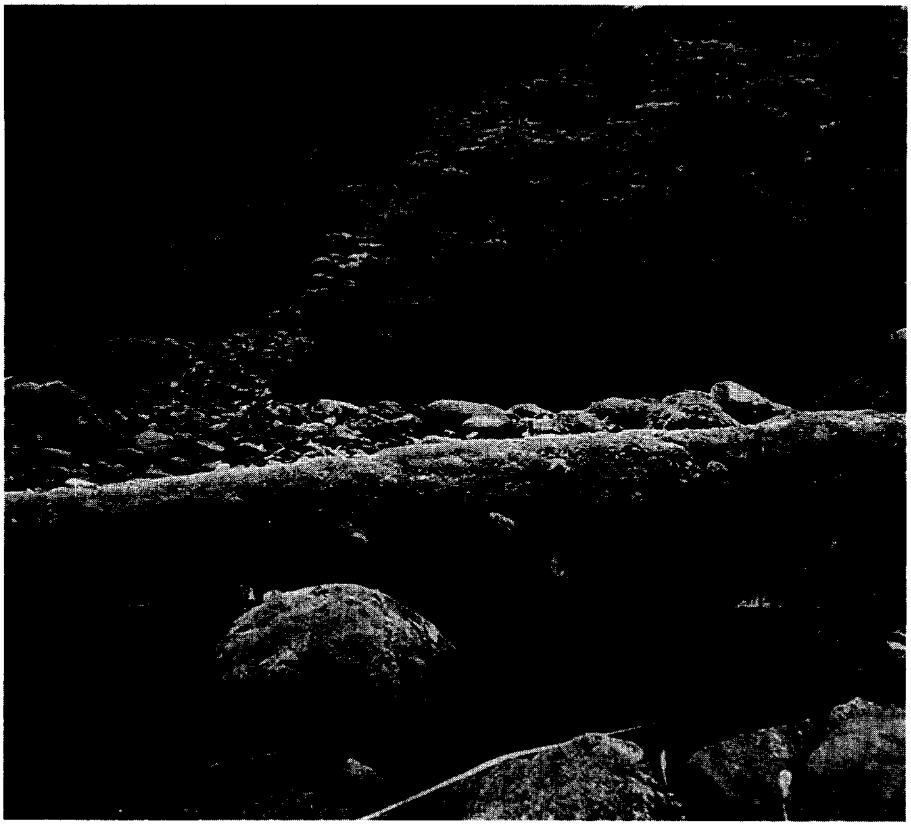

Fig. 4. Large woody debris along a steep channel, 0.14 slope. Note vegetation colonization upon nurse logs and colluvial/alluvial sediments. LWD traps both colluvium and alluvium creating an elevated substrate on which vegetation has colonized and established.

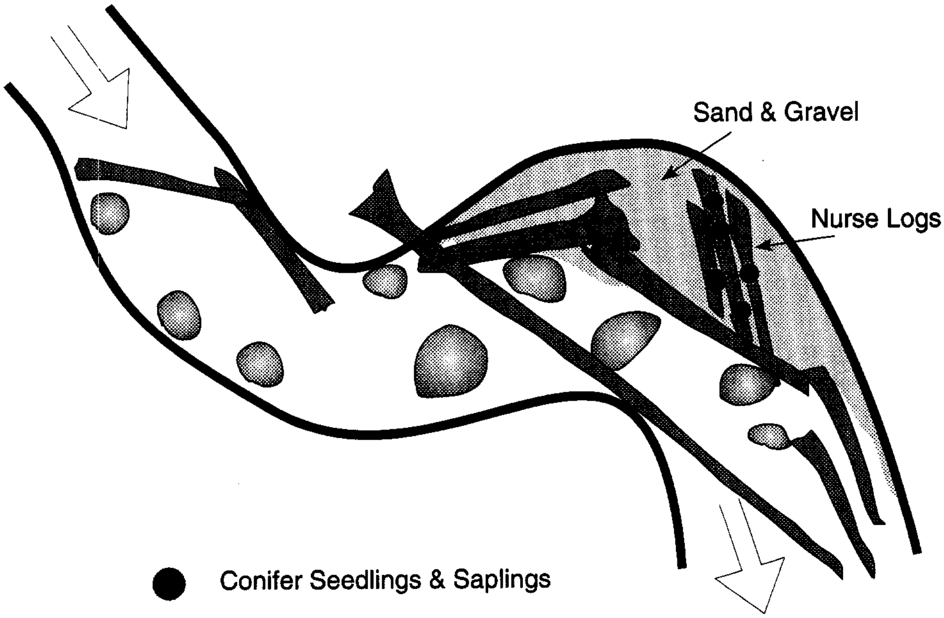

Fig. 5. Plan view of Fig. 4. Note depositional formation and LWD serving as nurse logs.

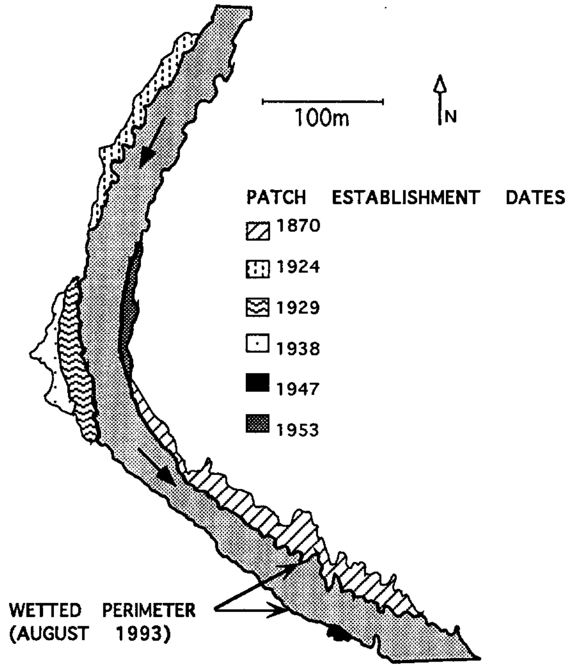

Fig. 6. Confined alluvial channel. Plan view with vegetation patch minimum ages (Fetherston and Naiman, unpubl. data). Note lack of LWD accumulations. Queets River, Washington, USA.

successional dynamics of riparian vegetation. The first occurrence of a relatively stable forested floodplain (i.e., an active vegetated floodplain influenced by fluvial process and sediment deposition with a persistence of 10–100 years) within montane drainage networks in the Pacific Northwest is associated with LWD either parallel or oblique to the channel. LWD effectively traps both colluvium and fluvially transported sediment (Figs. 2, 4 and 5). In addition to creating depositional areas suitable for colonization and establishment of riparian vegetation, LWD functions as 'nurse logs' (Franklin, 1982; Harmon et al., 1986) upon which woody species colonize (Figs. 2, 4 and 5). Nurse logs provide > 90% of all conifer seedling colonization sites within mature forests on terraces of the South Fork Hoh River in the western Olympic Mountains, USA (McKee et al., 1984). Nurse logs provide elevated plant colonization sites off the forest floor minimizing competition between seedlings and other forest floor vegetation (Harmon et al., 1986). Nurse logs in locations subjected to frequent flooding provide sites enabling the establishment of plants unable to withstand saturated soil conditions, thus increasing riparian plant diversity (Pollack and Naiman, unpubl. data).

Riparian forests along alluvial channels can be divided into confined and unconfined channel types (Figs. 6 and 7; Fetherston and Naiman, unpubl. data). The degree of channel confinement restricts the development of an active forested floodplain. Additionally, as channel confinement increases, the influence of LWD upon riparian forest distribution decreases due to the decrease in area of active floodplain (Fig. 6). In unconfined channels, active floodplains are larger and less prone to inundation and scour enabling the establishment of vegetation capable of withstanding fluvial disturbances (Newton et al., 1968; Fig. 7). It is the systematic distribution of physical processes (i.e., avalanche, debris flow, and flooding), flood duration, and LWD accumulation through the network that is reflected in the network patterns of riparian vegetation.

9. Vegetation colonization and establishment — LWD and physical process

Vegetation colonizing the active channel and floodplain must survive flood scouring (Walker et al., 1986; Harris, 1987). The fraction of the stream's energy available to mobilize the bed, thus available to disturb vegetation, is a function of the total channel roughness. The total channel roughness includes such factors as (1) resistance to flow by bed-forming particles, (2) bedforms, (3) in-channel obstructions (e.g. LWD), and (4) turbulent mixing and hydraulic jumps (Montgomery and Buffington, 1993). The total force a stream exerts on its boundaries may be significantly reduced by these factors. This can be seen in Fig. 2 where the reduction in boundary shear stress due to the alteration of stream flow around the LWD accumulation is reflected in the attendant grain size distribution and pattern of vegetation establishment. Bed mobilization during bankful discharge (i.e., scouring effects) appears to cause significant fluvial disturbance of seedlings and established vegetation (Sigafoos, 1964; Harris, 1987). Seedlings in the active channel and unvegetated areas of the floodplain are at far greater risk to flood scour than established patches of vegetation on the floodplain due to the increased shear resistance of vegetated floodplains (Smith, 1976).

Plant propagules typically colonize the active channel and floodplain in spring and early summer during declining discharge regimes in temperate mountain

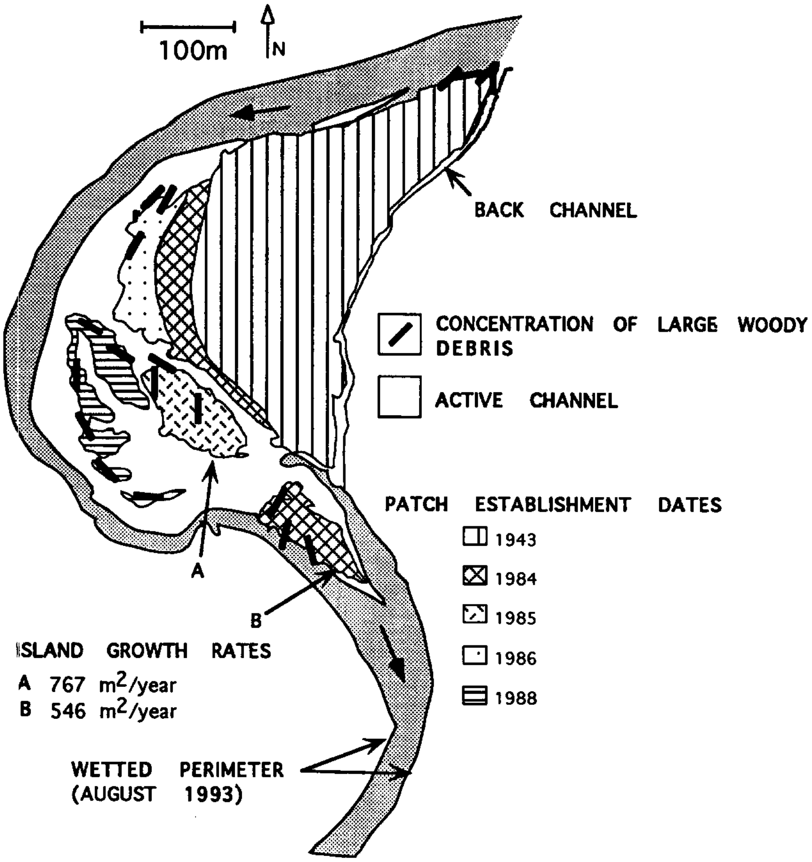

Fig. 7. Unconfined alluvial channel (Fetherston and Naiman, unpubl. data). Forest islands A and B established and are growing behind accumulations of LWD. If undisturbed these patches will coalesce with the floodplain mosaic. Queets River, Washington, USA.

river networks (Walker et al., 1986). Seed dispersal by dominant riparian woody species is adapted to the timing of regional climate regimes (e.g. *Salix spp*, *Populus spp*; Harris, 1987). Water stress during summer drought and physical disturbance during winter floods produce significant mortality within colonizing seedling populations (Walker et al., 1986). The scouring effect of flooding is known to be a significant disturbance affecting seedling colonization and establishment (Menges and Waller, 1983; Osterkamp and Hupp, 1984; Walker et al., 1986; Mitsch and Gosselink, 1993). The spatial distribution of vegetation over the active channel and floodplain along river networks of the western Olympic Mountains reflect the boundary shear stress distribution during floods (Figs. 2, 6 and 7). The detailed mechanics (i.e., contribution of plant roots to gravel bar shear resistance) of vegetation disturbance in gravel-bedded channels remain to be fully examined.

LWD deposition in the active channel or floodplain significantly alters local hydraulics, creating a low velocity zone immediately behind the LWD (Lisle, 1986; Abbe and Montgomery, 1995; Fig. 2). The colonization pattern illustrated in Fig. 2 and Fig. 7 reflect the local reduction in boundary shear stress and velocity created by LWD accumulations. The vegetation colonization patterns mirror the classic hydrodynamic streamlined form (Figs. 2 and 7). The forested floodplain in Fig. 7 is composed of numerous forest islands originating behind LWD accumulations. Vegetation colonizes both LWD and low velocity zones associated with LWD growing into forested islands that if left undisturbed will coalesce into a greater forested floodplain. Forest islands A and B in Fig. 7, both associated with LWD accumulations, have streamlined forms reflecting the underlying boundary shear stress field. These islands exhibit rapid NET growth rates of 767 $m^2\ yr^{-1}$ and 546 $m^2\ yr^{-1}$ respectively. NET island

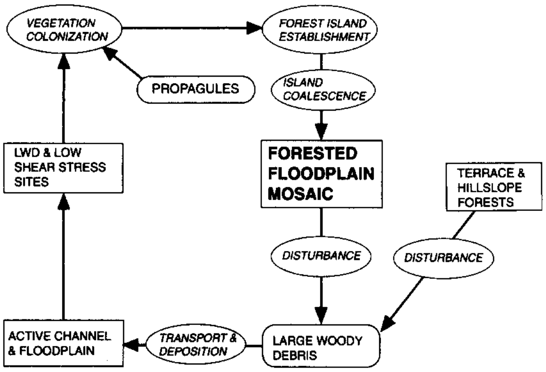

Fig. 8. Conceptual model of montane riparian forest development.

growth includes total plant colonization and disturbance as reflected by the total island area and the oldest island tree date of origin. The age structure of the forested floodplain then, reflects both the history of LWD deposition and fluvial disturbance (Fig. 6 and Fig. 7).

10. LWD, physical process and riparian forest development in montane river networks — a biogeomorphic process

LWD accumulations are sites of initial plant colonization within the developing forested floodplain (Figs. 2 and 7). Hillslope and fluvial processes are systematically distributed through the network. These geomorphic processes are reflected in riparian forest structure, composition, and spatial distribution unique to each process region (i.e., debris-flow-avalanche, debris-flow-fluvial, fluvial; Fig. 1). Fig. 8 is a simple conceptual model of the role LWD plays in montane riparian forest development. LWD is recruited from hillslope, terrace, and floodplain forests by wind and the dominant hillslope and fluvial disturbance types (Fig. 1). Fluvial process drives LWD recruitment through channel meandering and attendant bank undercutting, mass failure, and input of trees. LWD is recruited through this process to the channel where it is transported and deposited on downstream active channels or floodplains. LWD forms accumulations, vegetation colonizes, forest islands establish and may grow over time if undisturbed. The larger the forest island the greater the local roughness factor resulting in a greater reduction of downstream boundary shear stress. This feedback process creates further low shear environments suitable for vegetation colonization (Fig. 8).

The aerial extent and structural complexity of the forested floodplain is constrained by valley morphology. The process of channel meandering creates a complex of abandoned back channels, high flow channels, and a variable forested floodplain mosaic. In natural river networks low gradient river segments have abundant LWD distributed in large accumulations forming depositional areas that provide sites for future floodplain vegetation to colonize (Sedell et al., 1988). The development of the forested floodplain in natural unlogged montane river networks occurs through a unique biogeomorphic feedback process. Trees of large stature are recruited to the channel where they are acted upon by fluvial and hillslope geomorphic processes. These accumulations of LWD form depositional sites where vegetation colonize and become established within an otherwise inhospitable fluvial environment. Network patterns of (1) hillslope and fluvial process, (2) LWD recruitment and deposition, and (3) vegetation colonization and establishment all contribute to the biogeomorphic feedback process of forested floodplain development in the montane river networks of the Pacific Northwest.

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